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Forward-Looking WDM Network Reconfiguration with Per-Link Congestion Control

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Abstract We study reconfigurations of wavelength-routed Wavelength Division Multiplexing (WDM) networks in response to lightpath demand changes, with the objective of servicing more lightpath demands without additional network resources from a long-term network operation point of view. For the reconfiguration problem under study, we assume WDM network operators are provided with lightpath demands in batches. With limited network resources, our problem has two unique challenges: balancing network resource allocations between current and future lightpath demands, and modeling future lightpath demands. The first challenge implies making tradeoffs between accepting as many current immediate lightpath demands as possible and reserving a certain amount of network resources for near future predicted lightpath demands. The second challenge implies modeling future predicted lightpath demands, which are not exactly known or certain as the current lightpath demands. Our proposed model allows a natural separation between the operation of the optical layer and the user traffic layer (predominantly the IP-layer), while supporting their interactions, for which we propose a new formulation for per-link congestion control, associated with a mathematical solution procedure. Our simulation results reveal that by properly controlling resource allocations in the

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current session using our proposed mechanism, rejections in future sessions are greatly reduced.

Keywords Optical networks · Traffic engineering · Load balancing · Traffic models · WDM network planning

1 Introduction

We study reconfigurations of wavelength-routed Wavelength Division Multiplexing (WDM) networks in response to lightpath demand changes, with the objective of servicing more lightpath demands without additional network resources from a long-term network operation point of view. The lightpath demands are provided to WDM network operators in batches. For each batch of lightpath demands, WDM network operators conduct a session of network resource allocations and lightpath provisioning. Compared with the previous batch of lightpath demands, which have already been handled in the previous session and among which accepted demands have been routed as lightpaths, the current batch may have increased or reduced lightpath demands between any given node pair. We propose a mathematical model and an algorithm for network operators to decide the acceptance or rejection of the increased lightpath demands, the selection of existing lightpaths to be removed for the decreased demands, and the allocation of network resources to the newly accepted demands.

Our problem has two unique challenges, i.e., (1) Balancing network resource allocations between current and future lightpath demands; and (2) Modeling future lightpath demands. The first challenge demands a tradeoff between accepting as many current immediate lightpath demands as possible and reserving a certain amount of network resources for near future predicted lightpath demands. The second challenge requires modeling future predicted lightpath demands, which are not exactly known or certain as current lightpath demands. These two unique challenges are not addressed in the previous study [1]. In addition to the above two unique challenges, our problem needs to handle two traditional decision/optimization problems, i.e., Routing and Wavelength Assignment (RWA) problem for newly accepted demands, and selecting existing lightpaths to be removed for decreased demands. Specifically, when the requested number of lightpaths is reduced between a given node pair, a different selection of existing lightpaths to be removed results in different network resources being released, because existing lightpaths between the same node pair may use different paths or wavelength channels.

Our proposed model allows a natural separation between the operation of the optical layer and the user traffic layer (predominantly the IP-layer), while supporting their interactions. Essentially, service providers send lightpath demands to WDM network operators, who use the demands as an input, and decide the acceptance/rejection of lightpath demands (e.g., [2–9]). Then, lightpaths are provisioned for the accepted demands. Since WDM network operators normally keep the lightpath rejection rate relatively low (e.g., below 10%), the provisioned lightpaths meet the requests very well, although not perfectly. For the next batch, the service providers may request a modified set of lightpath demands. As time moves on, this process iterates to adapt to the service providers' changing requirements. Compared to the previous studies that allow reconfigurations of traffic-carrying existing lightpaths by re-routing them along a different path (e.g., [2–9]), changing their wavelength channels (e.g., [4–9]), adding or removing IP-layer processing in the middle (e.g., [4]), our proposal does not change any existing lightpaths, unless the number of lightpath demands is reduced in the current session. Thus, we do not disrupt the customer traffic as a result of WDM network reconfigurations. Unlike some existing methods that incorporated traffic prediction into the WDM network reconfigurations [10–14], our method does not predict traffic and takes lightpath demands as input for the purpose of separating the operation of the optical and user traffic layers.

In the literature, WDM network reconfigurations have been extensively studied in different contexts and under different reconfiguration strategies (see survey [15]). For integrated IP-over-WDM networks, adaptive WDM network reconfigurations were proposed to be triggered by realtime measured performance metrics, e.g., carried user traffic on lightpaths [16–24], average lightpath hop number of user traffic [25], capacity on any alternative route between a given pair of routers [26], the gain of "network efficiency" measured by the additional fraction or multiple of the previous traffic demands that can be accommodated by the network [27], blocking of arrival user traffic flows [9, 28], and blocking of lightpath requests [29–32]. Generally, the adaptive WDM network reconfigurations result in service disruptions, although efforts are made to minimize such disruptions, e.g., in [16]. In addition, it is questionable whether WDM network operators are allowed or able to monitor the user traffic carried by lightpaths. Transparent WDM networks, which are ignorant to data format and protocols, have certain operational advantages [33]. Another strategy of WDM network reconfigurations aimed at designing WDM networks insensitive to traffic changes, which can be classified into two flavors: universal virtual topology [34–38], and over-provisioning [39–41]. Both of them suffer from sub-optimal network operation most of the time, or from limiting allowed future traffic patterns.

WDM network reconfiguration consists of three phases [42]: (1) making a policy decision whether a reconfiguration should be conducted; (2) selecting a set of lightpath demands to be accepted, based on certain optimization objectives; and (3) migrating from the current lightpath deployment to the newly generated lightpath provisioning plan. We propose a decision/optimization algorithm aiming at providing network operators a method to evaluate the tradeoffs in the second phase, i.e., selecting lightpath demands to be accepted, and assess the impact of different decisions on the network operation objectives. Our proposed algorithm may be used periodically or as needed. The outcome of our algorithm is a new lightpath provisioning plan, together with the acceptance decisions of lightpath demands, and removal choices of existing lightpaths for decreased demands. Since the new lightpath provisioning plan generated by our algorithm guarantees no service disruption to existing lightpaths, the third phase becomes trivial. As long as the lightpaths used by the reduced demands are removed before the establishment of new lightpaths, neither the sequence of setting up new lightpaths nor the centralized or distributed methods of lightpath establishments matters.

The contributions of this paper include:

(1) Non-disruption WDM network reconfigurations. No re-routing is allowed and no existing lightpaths are removed unless lightpath demands between a given node pair are decreased. In this way, there is no disruption to the previously committed lightpath services.
(2) A practical model for network operators to describe current and future lightpath demands. Our proposed model is able to describe accurate current lightpath demands and uncertain future lightpath demands. The uncertainty of future lightpath demands is modeled as per-link congestion control information.
(3) Formulation of the WDM network reconfiguration problem with a capability of balancing network resource allocations to current and future lightpath demands.
(4) Performance evaluations that demonstrate the advantage of such per-link congestion control. We obtain numerical results by using Lagrangian Relaxation and Sub-gradient Methods (LRSM) to solve our proposed model. Compared to heuristic algorithms, our solution method is able to obtain bounds to quantify the optimality of near-optimal solutions.

This paper is organized as follows: in Sect. 2, we summarize existing techniques in modeling lightpath demands, and propose our model that describes the uncertainty of future predicted demands using per-link congestion control. In Sect. 3, we provide a simple illustration to demonstrate the advantage of using a proper per-link congestion control in reducing the number of rejections in future reconfigurations. In Sect. 4, we describe our problem formulation, followed by Sect. 5 showing performance evaluation results. We conclude this paper in Sect. 6. Our solution method using LRSM is outlined in "Appendix".

2 Modeling Lightpath Demands

2.1 Pipe Model versus Hose Model

The pipe model is widely used to describe lightpath demands, which specifies lightpath demands between all node pairs and usually using a matrix format. The pipe model is effective in describing precisely and accurately the lightpath demands (e.g., used in [2–9]). However, in modeling future lightpath demands, the pipe model cannot effectively handle the uncertainty of future lightpath demands.

The hose model is flexible in describing bandwidth demands, where each node is associated with a pair of bandwidth demands, i.e., ingress and egress bandwidth demands. The ingress bandwidth demand of a node specifies the total incoming traffic from all other nodes, and the egress bandwidth demand is the total amount of traffic that this node can send to other nodes [43–47]. The hose model has advantages over the pipe model [44, 47]:

- Ease of specification: Each node only needs to specify a pair of ingress and egress bandwidth demands, instead of inbound and outbound bandwidth demands from/to all other nodes;
- Flexibility: Each node's ingress and egress bandwidth demands may be arbitrarily distributed over all other nodes, so long as the ingress and egress bandwidth demands of each node are not violated;
- Multiplexing gain: Statistical multiplexing offers opportunities to set less aggregate bandwidth demands for a given node than the total of the node's inbound or outbound bandwidth demands;
- Ease of characterization: Aggregated bandwidth demands are easier to be characterized than bandwidth demands of individual source–destination pairs.

Although the hose model is successfully used in IP networks, applying the hose model to WDM networks faces a special challenge, i.e., unlike IP networks, bandwidth demands in WDM networks use a granularity of lightpath. WDM differs from IP-layer multiplexing, requiring each wavelength channel in a fibre being used by only one lightpath, restricting the selection of incoming and outgoing wavelength channels at an intermediate switch constrained by the wavelength conversion, and restricting selections of outgoing and incoming wavelength channels at source and destination nodes constrained by transmitters and receivers. As a result, it is preferable to specify a WDM node's ingress and egress bandwidth demands for each port. In [47], full wavelength conversion was assumed in all WDM nodes to alleviate restrictions on wavelength channel selections. In [48, 49], traffic grooming was used to implement the proposed routing scheme of user connections with bandwidth below the capacity of a lightpath.

2.2 Previous Work in Modeling Uncertainty of Lightpath Demands

Several techniques were used in the previous work in modeling uncertainty of lightpath demands: proportional scale-up [27, 50], a set of possible future demand patterns [51, 52], and artificial demands [53, 54].

In the proportional scale-up model, although the exact future lightpath demands are unknown, presumably future lightpath demands are proportionally scaled up from the current lightpath demands [27, 50]. The rationale behind is that the distribution of lightpath demands remains similar, with the current lightpath demands being a good representation of the demand distribution. Similar to a road traffic model [55], the proportional scale-up model is efficient when lightpath demands are measured by aggregated bandwidth or average data rate. But, it is inefficient when lightpath demands are measured by the number of lightpaths, due to its coarse granularity. Moreover, it may not be always true in assuming that future demands are greater than the current ones for all node pairs.

Robust network capacity planning and routing design methods have been investigated for a pre-defined set of possible future demand patterns, with an estimated probability of occurrence [51, 52] for each pattern. In [51], stochastic programming was used to deal with demand uncertainty in a two-phase decision process, where the first phase considered the budget to be invested at present and the second phase represented the corrective or recourse actions to take place in the future. In [52], robust optimization was used to find solely a present decision minimizing the expected regret due to undesirable outcomes, aiming at creating a fairly good and robust design regardless of which demand pattern was realized. Both methods in [51, 52] are rooted from stochastic programming and suffer from the requirements of estimating the probability of occurrence of all demand patterns.

Artificial demands were used to represent potential extra demands on each node pair that could be served in [53], where demand uncertainty was modeled by projected demands, i.e., artificial and unknown future demands, with a rationale that maximizing the acceptance of the projected demands leads to enhanced readiness for future demands, when future demands follow the pattern of the projected demands. Similar to [53], the acceptance of potential extra lightpath demands was maximized in [54].

2.3 Our Proposed Model

We propose a model to describe lightpath demands in the current reconfiguration session, in which immediately known lightpath demands are modeled as a pipe model. Meanwhile the uncertainty of future predicted demands is modeled by per-link congestion control information. The timeline of reconfiguration sessions and their respective inputs and decision context are shown in Fig. 1. Unlike the hose model, our per-link congestion control information considers transit lightpath demands in addition to originating/terminating lightpath demands. Our per-link congestion control information is also defined for each WDM node port.

We will use Lagrangian relaxation and sub-gradient methods to solve our proposed model. The solution method will be briefly outlined in the "Appendix", and some more details can be found in [6]. In the Lagrangian relaxation framework, Lagrangian multipliers reflect the intensity of demands on resources, and at the

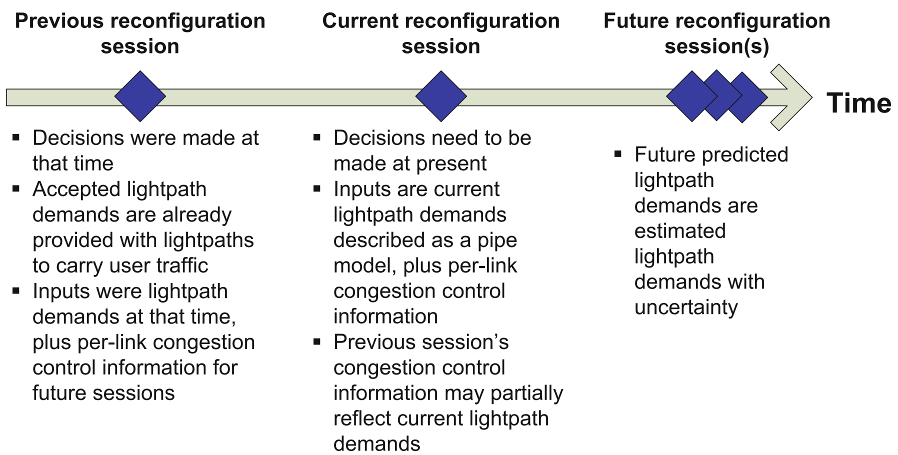

Fig. 1 Inputs to the current reconfiguration session include current lightpath demands described as a pipe model, plus per-link congestion control information

same time, indirectly relate to the distribution of future demands. In this way, although the distribution of future demands is not explicitly modeled as stochastic programming, our model together with LRSM indirectly contains similar information.

3 A Simple Case for Illustration

We show a simple example illustrating how a proper per-link congestion control can help reducing the number of rejections in the future reconfiguration. We consider a 5-node network with 8 wavelengths, as shown in sub-graph (a) in Fig. 2. The lightpath demand matrices of two consecutive sessions (subgraph (a) shows the current session and subgraph (b) shows the future session) are shown in Fig. 3, where the horizontal and vertical indexes are the source and destination nodes, respectively. Specifically, the number on the *i*th row and the *j*th column in a matrix represents the number of lightpath demands from node i to j (N_{ij}). Please note that the node counting starts from 0. In the current session (as seen in (a)), there are 8 lightpath demands between nodes 0 and 2 for both directions. In the future session [shown in (b)], the lightpaths demands between node pairs (1, 3) and (2, 3) increased to 8 for both directions, and we can see that the demand over links 2 and 4 becomes higher in the future session.

Now we shall compare the following two cases:

Case 3.1—Without per-link congestion control: The optimized solution for the current session is to use the full capacity on links 1 and 4. Since all capacity on

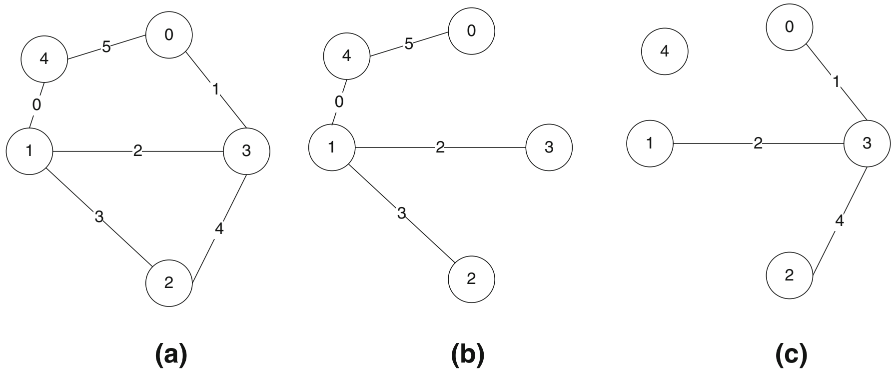

Fig. 2 Topologies of a 5-node network

Fig. 3 Lightpath demand matrices of current and future sessions

(a)

0	0	8	0	0
0	0	0	0	0
8	0	0	0	0
0	0	0	0	0
0	0	0	0	0

(b)

0	0	8	0	0
0	0	0	8	0
8	0	0	8	0
0	8	8	0	0
0	0	0	0	0

links 1 and 4 is depleted, for the future session, the network topology effectively becomes (b) in Fig. 2, on which the extra 32 demands will be routed. Obviously, 16 of them have to be rejected.

Case 3.2—With per-link congestion control: If we set the congestion penalty on the links that will be highly demanded in the future session, i.e., links 2 and 4, to be infinitely high (only as an example) in the current session, then the lightpath demands between nodes 0 and 2 (in the current session) will go through links 5, 0 and 3. The network topology for the future session effectively becomes (c) in Fig. 2 and all of the extra 32 demands can be accepted in the future session.

We can easily see from the comparison above that 16 extra lightpaths can be accepted in the future session if per-link congestion control is used in the current session.

4 Problem Formulation

4.1 Notations

For the remainder of this paper, the following notations and variables are used:

e_{ij}	The physical fibre between node i and node j; $e_{ij} \in E$;
f	The number of 'dummy' demands, which is equal to $u(X'_{sd} - N_{sd})$;
n_{ij}	An integer representing the number of wavelengths in the wavelength set W_{ij}. Note that $n_{ij} = n_{ji}$;
s, d	The source and destination, respectively, of a lightpath;
s_{sdn}	The nth new lightpath demand between (s, d);
t'_{sdn}	The nth existing lightpath between (s, d) from the previous session;
v	The degree of the wavelength conversion;
w_{ijc}	The cth wavelength channel on physical fibre e_{ij} $(0 < c \leq n_{ij})$;
A	The set of admission status of all the lightpath demand matrix, i.e., $\{\alpha_{sdn}\}$;
A_{sd}	The variable set $\{\alpha_{sdn}\}_{sd}$, the set of admission status of all the lightpath demands of (s, d);
B	The variable set $\{\beta_{sdn}\}$;
D	The number of source–destination pairs that have lightpath demands, but are not assigned any lightpath;
D_{sdn}	The total routing dual cost of s_{sdn};
E	The set representing all fibre links in the network;
F_{ic}	The number of wavelength converters that convert a signal from wavelength c to other wavelengths on node i;
l_{ij}	The penalty coefficient of congestion on link e_{ij};
H_{sd}	The integer equal to $\max(N_{sd}, X'_{sd})$;
$I_i(c)$	The set of wavelengths, to which the traffic from wavelength c can be converted on node i;
N	The number of nodes in the network;
N_{sd}	The number of lightpath demands between (s, d);

P_{sdk} Defined as $(P–(H_{sd}–k)S)$, $(k \geq 1)$, which means the penalty for rejecting one more lightpath demand of (s, d) when there are already k-1 lightpaths demands rejected. If $f > 0$, $P_{sd1} = P_{sd2} = \ldots = P_{sdf} = 0$;

$P_{sd}(k)$ The penalty coefficient for rejecting k lightpath demands of (s, d), which can be represented by $\sum_{h=1}^{k} P_{sdh}$. $P_{sd}(0) = 0$;

S The step size of rejection penalty coefficient for fairness consideration;

T The overall number of source–destination pairs that have the lightpath demands;

V The set representing all the nodes in the network;

(V, E) An undirected graph representing the DWDM network;

W The number of wavelengths used in the network;

W_{ij} The wavelength set $\{w_{ijc,}\ 0 < c \leq n_{ij}\}$ available in the physical link e_{ij};

X'_{sd} The number of existing lightpaths between (s, d) from the previous session;

Z The overall number of s_{sdn}'s in the network;

$*\alpha_{sdn}$ A 0–1 integer variable indicating the admission status of s_{sdn}, equal to zero, if s_{sdn} is rejected; one otherwise;

γ_{-ij} A variable representing the congestion on link e_{ij} $(0 \leq \gamma \leq 1)$;

δ_{ijc}^{sdn} A 0–1 integer variable, representing the use of wavelength channel w_{ijc} by lightpath s_{sdn}; (Note)

$\varphi_{j,ab}^{sdn}$ A 0–1 integer variable, representing the use of wavelength converters; (Note)

Δ_{sdn} The variable set $\{\delta_{ijc}^{sdn}\}_{sdn}$, representing the wavelength assignment for s_{sdn}; (Note)

Δ The variable set $\{\delta_{ijc}^{sdn}\} = \{\Delta_{sdn}\}$; (Note)

Φ_{sdn} The variable set $\{\varphi_{j,ab}^{sdn}\}_{sdn}$, representing the wavelength converter assignment for s_{sdn}; (Note)

Φ The variable set $\{\varphi_{j,ab}^{sdn}\} = \{\Phi_{sdn}\}$. (Note)

Note: We denote the variables/sets of lightpaths that are from the previous reconfiguration session with an apostrophe. For example, the notation Δ'_{sdn} represents the set Δ_{sdn} of the existing RWA of t'_{sdn}, which is assigned in the previous session.

The relationship between the number of demands (N_{sd}) and the number of existing lightpaths (X'_{sd}) between (s, d) is of great importance to the problem formulation. Therefore we use the same *Session Coordination Processing procedure* as in [6] to relate each *new lightpath demand* with one *existing lightpath* (relating each s_{sdn} with one t'_{sd}) in order to formulate the network reconfiguration and to facilitate a decomposition solution approach.

4.2 Coordination of Sessions

We denote the number of demands by N_{sd} and the number of existing lightpaths by X'_{sd}. We define the *new lightpath demands* as the demands to be established (might as well be rejected) in the current session and the *existing lightpaths* as the lightpaths already established in the previous session (including those to be abandoned). Note that only the accepted lightpath demands from the previous session are seen in the current session. To facilitate the illustration, we introduce the variable s_{sdn}, representing the nth new lightpath demand of source–destination pair (s, d). Let t'_{sdn} represent the nth existing lightpath of (s, d). Let α_{sdn} be a 0–1 integer variable, representing the rejection status of s_{sdn}, i.e., it has a value of 0, if s_{sdn} is rejected, and 1 if admitted. Note that all existing lightpaths are the lightpath demands that are accepted in the previous session ($\alpha'_{sdn} = 1$). For every (s, d), we denote the number of *new lightpath demands* as N_{sd} and the number of *existing lightpaths* as X'_{sd}. A variable $H_{sd} = \max\left(N_{sd}, X'_{sd}\right)$ is also introduced to relate the two adjacent sessions and to simplify the description.

We use the same session constraints as in [6] to define the capacity change between two sessions:

Rule 1 If the number of new lightpath demands between (s, d) is more than or the same as the number of existing lightpaths (i.e., $N_{sd} \geq X'_{sd}$), the lightpath demands accepted in the new session must not be fewer than the previous session

Rule 2 If there is less capacity demand in the new session between (s, d), i.e., $N_{sd} < X'_{sd}$, the lightpath demands accepted in the new session have to be equal to N_{sd}

These two rules (formulated in Constraint (e) later) avoid the drastic rearrangement in the optical layer, resulting in fewer disturbances in the upper layer traffic (e.g., TCP/IP packets), which only sees the virtual topology formed by the lightpaths, and more stable network performances. Note that when $N_{sd} = 0$, all existing lightpaths between (s, d) will be disconnected/terminated in the new session (according to Rule 2).

We use the following procedure as in [6] to associate each new lightpath demand with an existing lightpath:

(A) If $N_{sd} \geq X'_{sd}$, each new lightpath demand (s_{sdn}), with the index $0 < n \leq X'_{sd}$, corresponds to the existing lightpath t'_{sdn} and the s_{sdn}'s with $X'_{sd} < n \leq N_{sd}$ are not associated with any existing lightpath. ($H_{sd} = \max(N_{sd}, X'_{sd}) = N_{sd}$ new lightpath demands in total)

(B) If $N_{sd} < X'_{sd}$, we create $H_{sd} = \max(N_{sd}, X'_{sd}) = X'_{sd}$ new lightpath demands between (s, d) ($f = X'_{sd} - N_{sd}$ new lightpath demands are 'dummy' demands), and because that Constraint (e) confines that the eventual number of lightpaths accepted has to be equal to N_{sd}, the optimization result will not be influenced by introducing more 'dummy' demands.

With the procedure above, we can simply use $H_{sd} = \max(N_{sd}, X'_{sd})$ new lightpath demands for every (s, d) in the formulation.

4.3 Objective and Constraints

Our formulation is penalty-based, penalizing the rejection of demands and the congestion. Let $P_{sd}(k)$ be the penalty for rejecting k lightpath demands of (s, d). Generally, if there are k lightpath demands already rejected, the penalty for rejecting an extra demand is a constant value $P = P_{sd}(k+1) - P_{sd}(k)$. The readers are referred to [6] for a more detailed description of how to set these values to take fairness into consideration.

We shall penalize the congestion on each link individually, with a penalty function $G_{ij}(\gamma_{ij}) = l_{ij} \times \gamma_{ij}^2$, where l_{ij} is the congestion penalty coefficient and γ_{ij} $(0 \le \gamma_{ij} \le 1)$ is defined to be *congestion* (similar to [6]) of the link e_{ij} (see Constraints (c) later). Figure 4 provides a graphical view of the congestion penalization scheme. Please note that we only take this scheme as an example, since it is the simplest form to exert "higher pressure" when the congestion level is higher. Other penalty functions can also be easily accommodated.

4.3.1 Objective Function

Our objective function is to obtain

$$\min_{\mathrm{A,B,\Delta,\Phi,\Gamma}} \{J\}, \quad \text{where} \quad J \equiv \sum_{(s,d)} P_{sd}\left(\sum_{0<n\le H_{sd}} [1-\alpha_{sdn}]\right) + \sum_{(i,j)} G_{ij}(\gamma_{ij}). \quad (1)$$

The function J is the overall penalty consisting of the rejection penalty and the congestion penalty. The summation of $P_{sd}\left(\sum_{0<n\le H_{sd}} [1-\alpha_{sdn}]\right)$ is the total rejection penalty for the overall lightpath demand in the network, where $\sum_{0<n\le H_{sd}} [1-\alpha_{sdn}]$ is the number of rejected demands between (s, d). The second summation of $G_{ij}(\gamma_{ij})$ in the objective function represents the penalty for the congestion of each link. As seen in Constraint (c) later, it represents the percentage of the WCs used on a link.

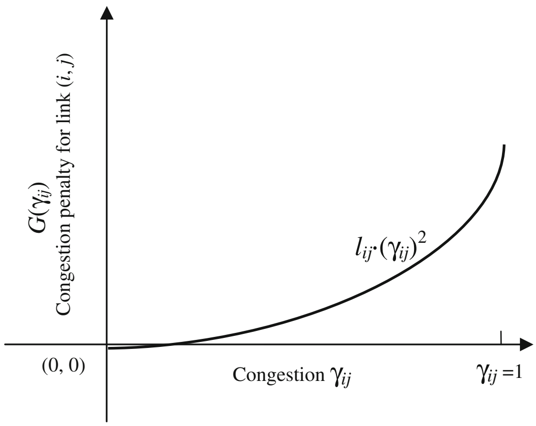

Fig. 4 Congestion penalty scheme

4.3.2 Constraints

The constraints can be classified into *General Constraints* and *Session Relationship Constraints*.

4.3.2.1 General Constraints General Constraints are used to confine the network operation in an independent session, just like those in the classic static RWA problems. Since the existing lightpaths are the accepted lightpath demands from the previous session, they also conform to the General Constraints.

(a) Lightpath flow continuity constraints:

Lightpath continuity means that if a demand is admitted, the lightpath assigned to it has to be continuous along the path between the source–destination pair. Since the assigned lightpath terminates at the two end nodes, we have

$$\sum_{j\in\mathcal{V}}\sum_{0<c\le n_{ij}}\delta_{ijc}^{sdn}-\sum_{j\in\mathcal{V}}\sum_{0<c\le n_{ji}}\delta_{jic}^{sdn}=\begin{cases}\alpha_{sdn} & \text{if}\quad i=s,\\ -\alpha_{sdn} & \text{if}\quad i=d,\forall(s,d),0<n\le H_{sd},\\ 0 & \text{otherwise},\end{cases}\tag{2}$$

where δ_{ijc}^{sdn} is a 0-1 integer variable, which equals to one if WC (wavelength channel) w_{ijc} is used by s_{-sdn}, and zero otherwise. Note that δ_{ijc}^{sdn} equals 0, if $\alpha_{sdn}=0$. If s_{sdn} is accepted, (i.e. $\alpha_{sdn}=1$) at the source node ($i=s$), there is one unit of flow going out of this node, thus Eq. (2) equals 1. At the destination node ($i=d$), there is a flow of 1 coming into this node, thus Eq. (2) equals -1. Finally, at the intermediate nodes, Eq. (2) equals 0 due to the conservation of flows. If the s_{sdn} is rejected (i.e., $\alpha_{sdn}=0$), Eq. (2) equals 0 at any node.

(b) Wavelength channel capacity constraints:

$$\sum_{(s,d)}\sum_{0<n\le H_{sd}}\delta_{ijc}^{sdn}\le 1\quad\forall(i,j),\quad 0<c\le n_{ij}\tag{3}$$

These constraints restrict every WC on a fibre to have only one lightpath routed in the same direction.

(c) Link congestion constraints:

$$\sum_{(s,d)}\sum_{0<n\le H_{sd}}\sum_{0\le c<n_{ij}}\delta_{ijc}^{sdn}\le\gamma_{ij}\left|W_{ij}\right|,\tag{4}$$

where W_{ij} denotes the wavelength set available in the physical link e_{ij}, γ_{ij} represents the congestion on link e_{ij} (note that $0\le\gamma_{ij}\le 1$) and $|\cdot|$ denotes the number of elements in the set. Since all links are assumed to have the same number of wavelengths, $|W_{ij}|=W$. These constraints have the same meaning as $W\gamma_{ij}=\sum_{(s,d)}\sum_{0<n\le H_{sd}}\sum_{0\le c<n_{ij}}\delta_{ijc}^{sdn}$. We use this formulation to facilitate our mathematical solution.

4.3.2.2 Session Relationship Constraints Session Relationship Constraints stipulate the relationship between the two consecutive sessions. In other words, the relationship between the existing lightpaths and the new lightpath demands.

(d) Non-rerouting constraints:

$$\Delta_{sdn} = \alpha_{sdn}\Delta'_{sdn} \quad \text{and} \quad 0 < n \le X'_{sd} \quad . \tag{5}$$

These constraints confine that no existing lightpath (routed from the previous session) can be rerouted, i.e., the new demand associated with this lightpath has to take the existing route and wavelength assignment. Otherwise it is rejected ($\alpha_{sdn} = 0$).

(e) Non-disconnection constraints:

$$\begin{cases} \sum\limits_{0 < n \le N_{sd}} \alpha_{sdn} = N_{sd}, & \text{if} \quad N_{sd} < X'_{sd} \\ \sum\limits_{0 < n \le N_{sd}} \alpha_{sdn} \ge X'_{sd}, & \text{if} \quad N_{sd} \ge X'_{sd} \end{cases} . \tag{6}$$

These constraints ensure that the bandwidth promised in the previous session is observed in the new session, by confining that the existing lightpaths (say t'_{sdn}) can be disconnected in the new session only when there are fewer lightpath demands between (s, d) in the new session. If there are more or the same number of lightpath demands between (s, d) in the new session, i.e., $N_{sd} \ge X'_{sd}$, the number of accepted new lightpaths cannot be fewer than the number of existing lightpaths ($\sum_{0<n\le N_{sd}} \alpha_{sdn} \ge X'_{sd}$); if there are fewer lightpath demands between (s, d) in the new session, i.e., $N_{sd} < X'_{sd}$, only ($X'_{sd} - N_{sd}$) lightpaths should be disconnected ($\sum_{0<n\le N_{sd}} \alpha_{sdn} = N_{sd}$).

5 Performance Evaluations

In this section, we shall demonstrate the performance of our algorithm on several computation examples. We will show first the effect of the localized congestion control in a single reconfiguration session. Then we shall use some real network cases to demonstrate the contribution of our per-link congestion control scheme by comparing the cases with or without per-link congestion control.

5.1 Effect of the Congestion Penalty Coefficient

We shall first show the capability of controlling the link congestion in a 14-node NSFNET topology as shown in Fig. 5 and shall test the computational complexity of the proposed algorithm. We assume that each link has only one fibre and each fibre has W WCs. The lightpath demands are shown in Fig. 6. Most of the results from our algorithm in the NSFNET example can be obtained within 10 min running

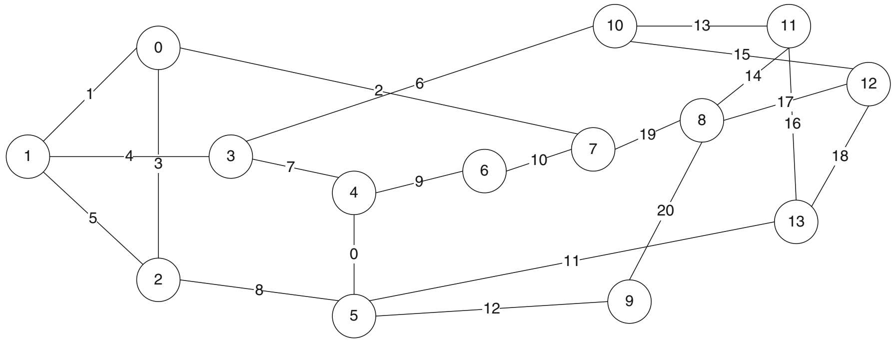

Fig. 5 NSFNET with 14 nodes and 21 links

Fig. 6 Lightpath demand matrix

0	0	2	1	3	2	0	3	2	2	1	0	2	1
1	0	3	3	1	0	2	1	0	2	0	1	0	1
0	3	0	2	0	2	3	0	3	2	1	0	2	1
2	2	0	0	0	3	2	0	1	3	0	2	2	0
0	3	2	1	0	3	2	3	2	0	3	0	2	3
1	1	0	3	2	0	3	0	1	2	3	2	0	3
0	2	1	2	0	3	0	1	0	3	2	0	3	0
1	3	1	0	2	2	3	0	0	1	3	0	2	2
1	3	0	3	3	0	1	0	0	1	3	0	1	2
0	2	3	0	1	1	3	0	2	0	1	3	0	3
3	1	2	0	2	0	1	3	0	3	0	1	0	0
0	3	0	2	3	0	2	0	1	0	3	0	2	3
0	2	1	0	3	2	0	3	0	1	3	3	0	3

on a personal computer with Windows XP®, Centrino® 2.0 GHz CPU and 1 GB of RAM. The computation time complexity is similar to the algorithm in [6] because the same LRSM framework is used. The readers are referred to [6] for more detailed computation time testing and the computation time reduction by reusing Lagrange multiplier values.

To simplify our study, we set the rejection penalty of the last connection demand for every (s, d) to the same value (although this is not required), i.e., $P_{sdk} = P$, $\forall k$. We change the congestion penalty coefficient of one link (we randomly pick $l_{2,5}$ and $l_{5,2}$ on link 8) and study the influence on the network behaviors. The congestion penalty coefficients of the other links (l_{ij}) are all set to zero. The remaining parameters are set to be $W = 16$ and $P = 100$. We can see in Fig. 7 that as $l_{2,5}$ and $l_{5,2}$ goes from 0 to 80,000, the final objective function first goes up very steeply and afterwards the change slows down, until eventually the curve flattens. At the same time, the congestion in both directions (see Fig. 8) shows similar behavior, i.e., the congestions drop drastically before the congestion penalty coefficients reach 10,000 and then slowly drop to 0 afterwards. At the value of 80,000, the congestion penalty

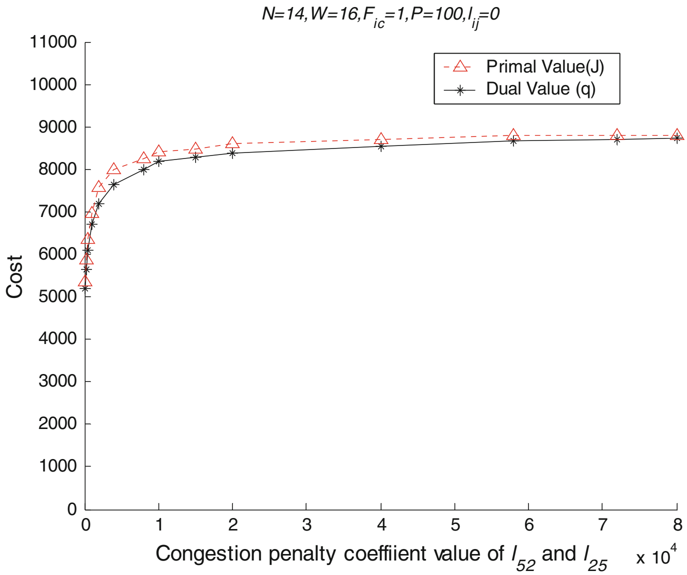

Fig. 7 Influence of l_{ij} on the final objective value

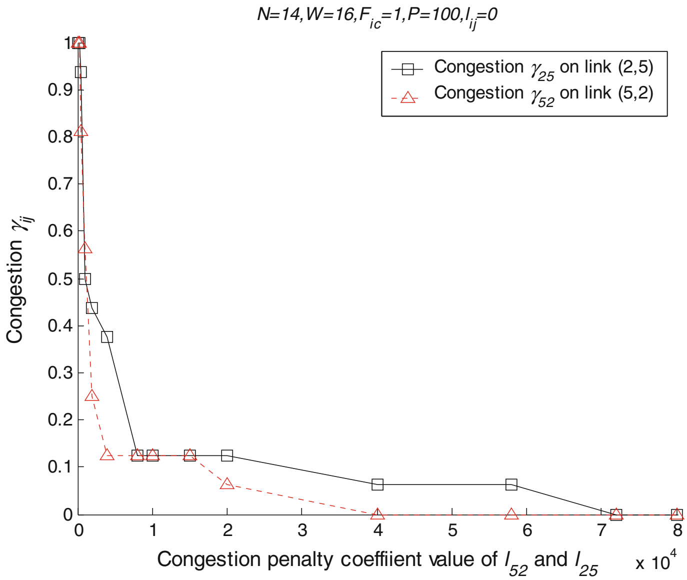

Fig. 8 Influence of l_{ij} on the controlled link congestion

is similar to an 'infinitely' large value (compared with the rejection penalty value), since no lightpath can 'afford' link 8 for this overly high congestion cost. We can see in Fig. 7 that our results are very close to optima, which are confined between the curve of the primal value and the curve of dual value (lower bound).

5.2 Example 1

We now study a 22-node network with 35 links shown in Fig. 9. The traffic matrices of the current session and of the future session are shown in (a) and (b), respectively, in Fig. 10. We use the following parameters: $F_{ic} = 1$, $W = 4$, $P = 100$, and $v = 4$. By comparing criticalities of the fibres resulting from the two matrices (as independent sessions), we can obtain the differences of the resources' criticalities between the current session and the future session. The criticality of a fibre, i.e., how critical it is needed by the overall lightpath demands, can be obtained by simply counting the number of demands that are routed on the fibre in the solution to the DP or by using Lagrange multipliers. The readers are referred to [56] for the detailed description of the criticality analysis using Lagrange multipliers. We pick 4 links (links 3, 24, 30, and 34) that have the highest criticalities in the future session to demonstrate the effectiveness of our algorithm. We now compare the case without any congestion control with the case with per-link congestion control. For either case, we shall optimize the current session (using the lightpath demand matrix in (a)) and obtain the RWAs. Then we optimize the future session (matrix in (b)) on the existing network configuration, i.e., the RWAs from the current session.

Case 5.2.1. Without Congestion Control: We first set all $l_{ij} = 0$, for the current session and conduct the RWA optimization. The number of rejected lightpaths we obtained is 0. The usages on links 3, 24, 30, and 34 are all 100%, for both directions.

Then we use the obtained network configuration from the current session to optimize the future session. The number of rejected lightpaths for the future session we obtained is then 32. The Lagrangian bound obtained is 30, which indicates that the optimum is between 30 and 32. The usages on links 3, 24, 30, and 34 are still 100%, for both directions.

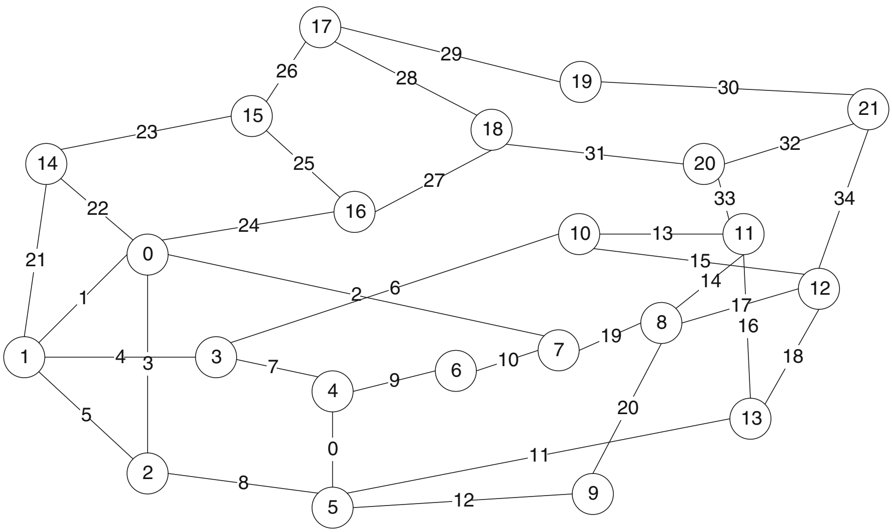

Fig. 9 A network with 22 nodes and 35 links

Fig. 10 Lightpath demand matrices for current and future sessions

0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	4	0	4	0	0	0	0	4	0	0	0	4	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	4	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a)

0	4	4	0	0	0	0	2	0	0	0	0	0	0	4	0	4	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	**4**	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	4	0	4	0	0	0	0	4	0	0	0	4	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	**4**	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0
4	0	**4**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	**4**	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	4	0	0	4	0

(b)

Case 5.2.2. With Congestion Control: We first set all congestion penalty coefficients on links 3, 24, 30, and 34 (i.e., $l_{0,2}$, $l_{2,0}$, $l_{19,21}$, $l_{21,19}$, $l_{0,16}$, $l_{16,0}$, $l_{21,12}$, and $l_{12,21}$) to an infinitely large value and set the remaining l_{ij}'s to 0, so that the usages on links 3, 24, 30, and 34 are all 0% for both directions. The number of rejected lightpaths we obtain is 2.

We then optimize the future session, using the network configuration of the current session. The number of rejected lightpaths is 8 and the Lagrangian bound is 7, which means our result is highly optimal.

We can see in Table 1 that the number of rejected demands in the future session dropped (32 − 8)/32 = 75%. Considering the lost (the extra number of rejected demands) in the current session, the actual gain in terms of percentage is (32-8-2)/32 = 68.75%.

Table 1 Rejections of lightpath demands in the 22-node network

	Rejections in the current session	Rejections in the future session	Total rejections
Without congestion control	0	32	32
With congestion control	2	8	10

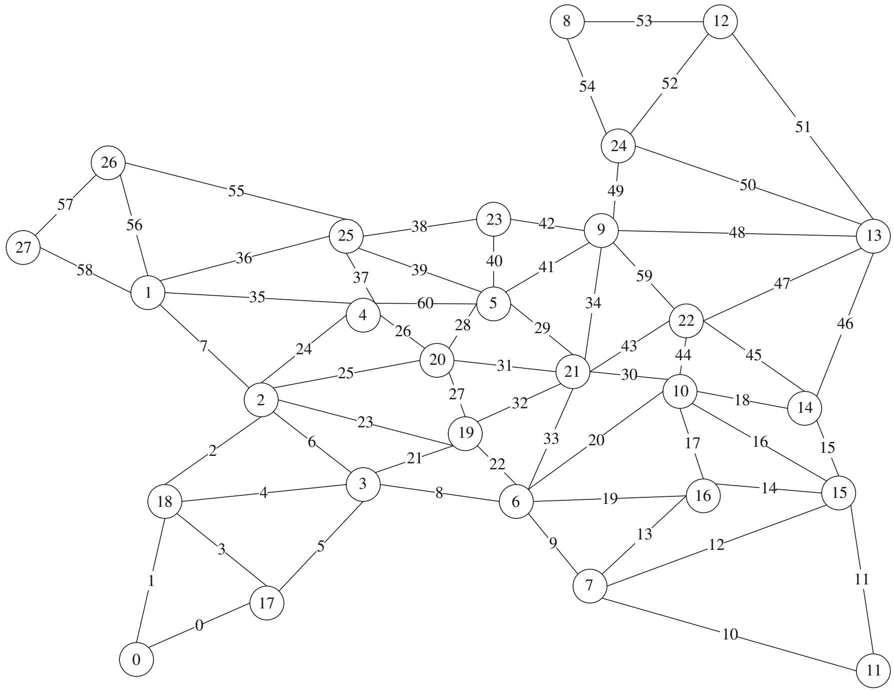

Fig. 11 A network with 28 nodes and 61 links

0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
1	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	2
4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	2	0	0
0	0	0	0	0	0	2	2	0	0	0	1	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0
0	4	1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	3	0	0	0	0	3	0	0	0	1	0	0	0	0	0	2	1	2	1	1	0	3	1	0
0	0	0	2	0	0	0	2	0	1	1	1	0	0	0	0	4	0	1	2	0	0	0	0	0	0	0	0
0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	3	1	0	4	0	0	0	0	0	0	0	0	0	0	1	1	0	1	1	0	1	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	1	4	4	3	0	0	1	0	3	1	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	[illegible]	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	0	1	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	1	1	0	3	0	0	0
0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0
0	0	0	0	0	0	0	4	0	0	4	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	4	1	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
0	0	4	4	1	2	4	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
0	0	1	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	4	0	0	0	0	0	0
0	0	0	0	0	2	1	0	0	0	1	0	0	1	1	0	0	0	0	1	4	0	1	0	0	0	0	0
0	0	0	0	0	1	0	0	0	1	1	0	0	1	3	0	0	0	0	0	0	1	0	1	0	0	0	0
0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	2	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	2
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	2
0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0

(a)

0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	**1**	0	0	**4**	0	0	**0**	0	0	0	0	1	0
1	0	**4**	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**2**	**4**	2
4	**4**	0	0	1	0	0	0	0	0	0	0	0	**1**	0	0	0	0	**4**	4	1	0	0	0	0	2	0	0
0	0	0	0	0	0	2	2	0	0	0	1	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0
0	4	1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	3	0	0	0	0	3	0	0	0	**0**	0	0	0	0	0	2	1	2	1	1	0	3	1	0
0	0	0	2	0	0	0	2	0	**2**	1	1	0	0	0	0	**0**	0	1	2	0	**4**	0	0	0	0	0	0
0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**4**	0	0	0
0	0	0	0	0	3	1	0	4	0	0	0	0	0	0	0	0	0	0	1	1	**4**	1	1	**4**	1	0	0
0	0	0	0	0	0	1	0	0	0	0	0	0	1	4	4	3	0	0	**0**	0	**2**	1	0	0	0	0	0
0	**1**	0	0	0	0	1	0	0	0	0	0	0	3	0	**4**	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	0	**0**	0	0	0	0	0	0	0	1	3	0	0	**4**	0	0	0	0	0	0	1	1	0	**4**	0	0	0
0	0	0	0	0	0	0	0	0	0	4	0	0	**4**	0	**4**	0	0	0	0	0	1	3	0	0	0	0	**1**
0	0	0	0	0	0	0	4	0	0	4	**4**	0	0	**4**	0	2	0	0	0	0	0	0	0	0	0	0	0
0	**0**	0	0	0	0	**0**	1	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	**0**	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
4	0	**4**	4	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
0	0	4	4	1	2	4	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0
0	0	1	0	2	0	0	0	0	1	**1**	0	0	0	0	0	0	0	0	1	0	**3**	0	**1**	0	0	0	0
0	0	0	0	0	2	**4**	0	0	**4**	**3**	**1**	0	1	1	0	0	0	0	**2**	**3**	0	**4**	0	0	0	0	0
0	**1**	0	0	0	1	0	0	0	1	**0**	0	0	1	3	0	0	0	0	0	0	**4**	0	1	0	0	0	0
0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	1	0
0	0	0	0	0	0	0	0	**4**	**4**	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	2	2	0	0	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	2
0	**4**	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	2
0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0

(b)

Fig. 12 Lightpath demand matrices for current and future sessions in the first lightpath demand pattern

5.3 Example 2

In this section, we shall study a larger network with 28 nodes and 61 links as shown in Fig. 11. There are 278 and 361 lightpath demands in the current and future sessions, shown in Fig. 12a, b, respectively. From the current session to the future session, there are 36 node pairs with increased lightpath demands, and 15 node pairs with slightly decreased lightpath demands. The changed lightpath demands are shown in bold font in the future session. The network parameters are set as: $F_{ic} = 1$, $W = 4$, $P = 100$, and $v = 4$. We pick 13 links ($LINKSET = \{1, 2, 7, 11, 15, 24, 33, 34, 37, 46, 49, 54, 56\}$) that have the highest criticalities in the future session and shall demonstrate the benefit of per-link congestion control.

Case 5.3.1. Without Congestion Control: We first set all $l_{ij} = 0$, for the current session and conduct the RWA optimization. The number of rejected lightpaths we obtain is 19. The usages on links in *LINKSET* are all 100%, for both directions.

Then we use the obtained network configuration from the current session to optimize the future session. The number of rejected lightpaths we obtain then is 69.

Table 2 Rejections of lightpath demands in the 28-node network under the first lightpath demand pattern

	Rejections in the current session	Rejections in the future session	Total rejections
Without congestion control	19	69	88
With congestion control	24	24	48

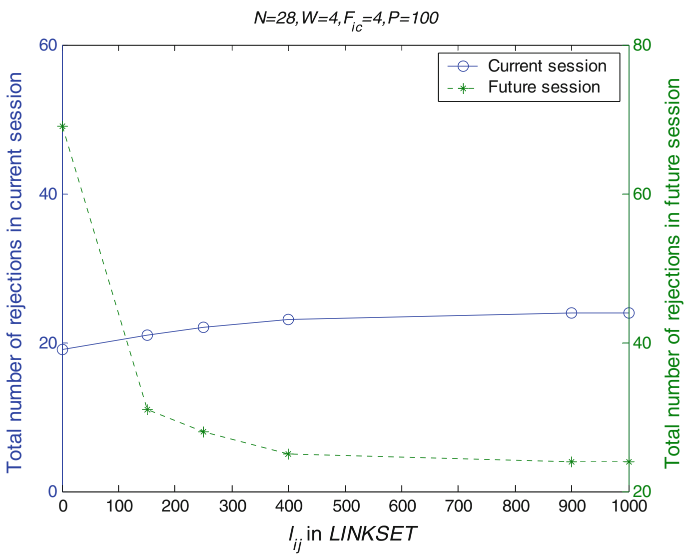

Fig. 13 Tradeoff of rejections in current and future sessions

The Lagrangian bound obtained is 51. The usages on links in *LINKSET* are still 100%, for both directions.

Case 5.3.2. With Congestion Control: We first set all congestion penalty coefficients on links in *LINKSET* to an infinitely large value and set the remaining l_{ij}'s to 0, so that the usages on links in *LINKSET* are all 0% for both directions. The number of rejected lightpaths we obtain is 25.

0	0	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
4	4	0	4	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0
0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	4	0	4	0	0
0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4	0	4	0	0	0
0	0	0	0	0	0	0	0	0	0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	3	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	0	0	4	0	0	0	0	0	0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	1
0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0
0	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
0	0	0	0	0	1	3	0	0	0	1	0	0	0	0	0	2	0	0	3	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0
0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	2	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(a)

0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	0	0	0	0
0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	4
4	4	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	4	1	1	0	0	1	0	0	0	0
0	0	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0
0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	4	0	0	0
0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	4	0	0	0	0	0
1	0	0	1	0	0	0	0	0	0	0	4	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	4	0	0	4	4	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	2	0	0	0	1	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
4	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	2	4	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	4	4	0	0	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	4	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b)

Fig. 14 Lightpath demand matrices for current and future sessions in the second lightpath demand pattern

We then optimize the future session, using the network configuration from the current session. The number of rejected lightpath is 25 and the Lagrangian bound is 20.

We can see from Table 2 that the number of rejected demands in the future session dropped (69 − 24)/69 = 65.2%. Considering the rejections in both sessions, the actual gain is (69 + 19 to 24 − 24)/(69 + 19) = 45.5%.

In Fig. 13, we demonstrate the trade-off between the current session and the future session by changing the congestion penalty in *LINKSET*. We can see that the biggest gain in the future session is from 0 to 400, i.e., in this range, very little sacrifice in the current session can result in a large number of not rejected requests in the future session.

5.4 Example 3

We use the same network with 28 nodes and 61 links as shown in Fig. 11, but impose a second lightpath demand pattern. The traffic matrices of the current and future sessions are shown in Fig. 14a, b, respectively. There are 203 lightpath demands in the current session and 224 lightpath demands in the future session. We conduct a per-link congestion control for 7 selected links (*LINKSET* = {35, 58, 49, 54, 1, 2, 11}), which based on operator's prediction will have high demand in the immediate future session. The number of rejected lightpath demands is given in Table 3, which shows a clear advantage of fewer total rejections when our proposed per-link congestion control is used.

6 Conclusions

We proposed a method to minimize the number of rejected lightpath demands in future WDM network reconfigurations by conducting a per-link congestion control in the current WDM network reconfiguration. Our method provides a tool for network operators to balance network resource allocations to current and future lightpath demands, and to describe accurate current lightpath demands and uncertain future lightpath demands. We used the Lagrangian relaxation and subgradient methods to solve our formulated problem, and demonstrated that in several examples preserving wavelength channels on properly selected links that will likely be congested in future WDM network reconfigurations, the total number of rejections is drastically reduced.

Table 3 Rejections of lightpath demands in the 28-node network under the second lightpath demand pattern

	Rejections in the current session	Rejections in the future session	Total rejections
Without congestion control	10	30	40
With congestion control	15	12	27

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Appendix: Solution Methodology

By properly relaxing some constraints using Lagrange multipliers, we will derive in this section the DP (Dual Problem), which can be decomposed into subproblems that can be solved independently. A schematic depiction of the overall algorithm is given in Fig. 15.

The LR Solution Procedure

We first use the Lagrange multipliers ξ_{ijc}, λ_{ic}, π_{ij} to relax respectively the wavelength channel capacity constraints (b), and link congestion constraints (c). This leads to the following Lagrangian **DP** (Dual Problem):

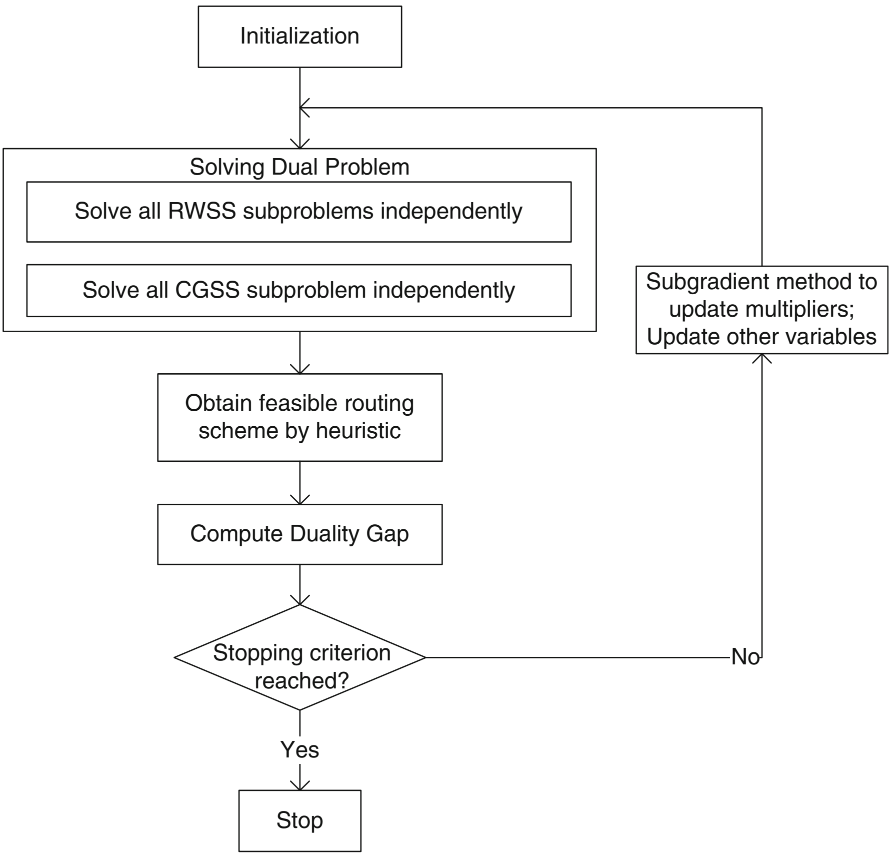

Fig. 15 Schematic depiction of the overall algorithm

$$\max_{\xi,\lambda,\pi\geq 0} q = \min_{\mathrm{A,B,\Delta,\Phi,\Gamma}} \left\{ \sum_{(s,d)} \left[P_{sd} \left(\sum_{0<n\leq H_{sd}} [1-\alpha_{sdn}] \right) \right] \right.$$
$$+ \sum_{(i,j)} G_{ij}(\gamma_{ij}) + \sum_{(i,j)} \sum_{0<c\leq n_{ij}} \xi_{ijc} \left(\sum_{(s,d)} \sum_{0<n\leq H_{sd}} \delta_{ijc}^{sdn} - 1 \right)$$
$$+ \sum_{i\in\mathcal{V}} \sum_{0\leq c<W} \lambda_{ic} \left(\sum_{(s,d)} \sum_{0<n\leq H_{sd}} \sum_{j\in\mathcal{V}} \sum_{0\leq a<n_{ij}} \varphi_{i,ca}^{sdn} - F_{ic} \right)$$
$$\left. + \sum_{(i,j)} \pi_{ij} \left(\sum_{(s,d)} \sum_{0<n\leq H_{sd}} \sum_{0\leq c<n_{ij}} \delta_{ijc}^{sdn} - \gamma_{ij} W \right) \right\},$$

subject to the constraints (a), (d), and (e), where ξ, λ, π are respectively the vectors of Lagrange multipliers $\{\xi_{ijc}\}$, $\{\lambda_{ic}\}$, $\{\pi_{ij}\}$.

After regrouping the relevant terms, the dual function leads to the following problem:

$$\min_{\mathrm{A,B,\Delta,\Phi,\Gamma}} \left\{ \sum_{(s,d)} \left[P_{sd} \left(\sum_{0<n\leq H_{sd}} [1-\alpha_{sdn}] + \sum_{(i,j)} \sum_{0<c\leq n_{ij}} \delta_{ijc}^{sdn} \left(\xi_{ijc} + \pi_{ij} \right) \right. \right. \right.$$
$$\left. \left. + \sum_{i\in\mathcal{V}} \sum_{0\leq c<W} \sum_{j\in\mathcal{V}} \sum_{0\leq a<n_{ij}} \lambda_{ic} \varphi_{i,ca}^{sdn} \right) \right] - \sum_{(i,j)} \sum_{0<c\leq n_{ij}} \xi_{ijc} - \sum_{i\in\mathcal{V}} \sum_{0\leq c<W} \lambda_{ic} F_{jc} \quad (7)$$
$$\left. + \sum_{(i,j)} \left(G_{ij}(\gamma_{ij}) - W\gamma_{ij}\pi_{ij} \right) \right\}.$$

By using the fact that $\delta_{ijc}^{sdn} = \alpha_{sdn}\delta_{ijc}^{sdn}$ and $\varphi_{i,ca}^{sdn} = \alpha_{sdn}\varphi_{i,ca}^{sdn}$, we can rewrite (7) as:-

Since the last two terms are independent of the decision variables (i.e., A, B, Δ, Φ, and Γ), the problem can be further simplified as:

$$\min_{\mathrm{A,B,\Delta,\Phi}} \left\{ \sum_{(s,d)} \left[P_{sd} \left(\sum_{0<n\leq H_{sd}} [1-\alpha_{sdn}] \right) \right. \right.$$
$$\left. \left. + \sum_{0<n\leq H_{sd}} \alpha_{sdn} \left(\sum_{(i,j)} \sum_{0<c\leq n_{ij}} (\xi_{ijc} + \pi_{ij}) \delta_{ijc}^{sdn} + \sum_{i\in\mathcal{V}} \sum_{0\leq c<W} \sum_{j\in\mathcal{V}} \sum_{0\leq a<n_{ij}} \lambda_{ic} \varphi_{i,ca}^{sdn} \right) \right] \right\}$$
$$+ \min_{\Gamma} \left\{ \sum_{(i,j)} \left(G_{ij}(\gamma_{ij}) - W\gamma_{ij}\pi_{ij} \right) \right\}$$
$$= \sum_{(s,d)} \min_{\mathrm{A}_{sd}} \left\{ P_{sd} \left(\sum_{0<n\leq H_{sd}} [1-\alpha_{sdn}] \right) \right.$$

$$+\sum_{0<n\le H_{sd}}\Bigg[\alpha_{sdn}\cdot\min_{\beta_{sdn},\Delta_{sdn},\Phi_{sdn}}\Bigg(\sum_{(i,j)}\sum_{0<c\le n_{ij}}(\xi_{ijc}+\pi_{ij})\delta_{ijc}^{sdn}$$
$$+\sum_{i\in\mathcal{V}}\sum_{0\le c<W}\sum_{j\in\mathcal{V}}\sum_{0\le a<n_{ij}}\lambda_{ic}\varphi_{i,ca}^{sdn})]\}+\sum_{(i,j)}\min_{\gamma_{ij}}\{G_{ij}(\gamma_{ij})-W\gamma_{ij}\pi_{ij}\},\qquad(8)$$

which we shall refer to as the **RP** (Relaxed Problem).

A.2. Decomposed Subproblems

We can see that the RP is composed of two minimization subproblem sets. The first subproblem set **RWSS** (Routing and Wavelength-assignment Subproblem Set) is

$$\sum_{(s,d)}\min_{A_{sd}}\Bigg\{P_{sd}\Bigg(\sum_{0<n\le H_{sd}}[1-\alpha_{sdn}]\Bigg)$$
$$+\sum_{0<n\le H_{sd}}\Bigg[\alpha_{sdn}\cdot\min_{\beta_{sdn},\Delta_{sdn},\Phi_{sdn}}\Bigg(\sum_{(i,j)}\sum_{0<c\le n_{ij}}(\xi_{ijc}+\pi_{ij})\delta_{ijc}^{sdn}$$
$$+\sum_{i\in\mathcal{V}}\sum_{0\le c<W}\sum_{j\in\mathcal{V}}\sum_{0\le a<n_{ij}}\lambda_{ic}\varphi_{i,ca}^{sdn}\Bigg)\Bigg]\Bigg\},\qquad(9)$$

subject to the constraints (a), (d), and (e). RWSS can be decomposed into source–destination-level sub-problems (denoted as $\mathbf{SDS_{sd}}$), each corresponding to one (s, d):

$$\mathrm{SDS_{sd}}=\min_{A_{sd}}\Bigg\{P_{sd}\Bigg(\sum_{0<n\le H_{sd}}[1-\alpha_{sdn}]\Bigg)+\sum_{0<n\le H_{sd}}\alpha_{sdn}\cdot I_{\mathrm{sdn}}\Bigg\},\qquad(10)$$

where I_{sdn} (corresponding to every s_{sdn}) is defined as

$$I_{\mathrm{sdn}}=\min_{\beta_{sdn},\Delta_{sdn},\Phi_{sdn}}\Bigg\{\sum_{(i,j)}\sum_{0<c\le n_{ij}}(\xi_{ijc}+\pi_{ij})\delta_{ijc}^{sdn}+\sum_{i\in\mathcal{V}}\sum_{0\le c<W}\sum_{j\in\mathcal{V}}\sum_{0\le a<n_{ij}}\lambda_{ic}\varphi_{i,ca}^{sdn}\Bigg\},\qquad(11)$$

subject to the constraints (a), (d), and (e). In RWSS, there are altogether Z lightpath-level subproblems (I_{sdn}'s) independent of each other.

In the subproblem set **CGSS** (Congestion Subproblem Set), there are E independent subγproblems, each corresponding to one network link:

$$\sum_{(i,j)}\min_{0\le\gamma_{ij}\le 1}\{G_{ij}(\gamma_{ij})-\gamma_{ij}W\pi_{ij}\}\qquad(12)$$

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